Promoting the production of salinized cotton field by optimizing water and nitrogen use efficiency under drip irrigation

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Abstract: Cotton is the main economically important crop in Xinjiang, China, but soil salinization and shortage of water and nutrients have restricted its production. A field experiment was carried out in the salinity-affected arid area of Northwest China from 2018 to 2019 to explore the effects of nitrogen and water regulation on physiological growth, yield, water and nitrogen use efficiencies, and economic benefit of cotton. The salinity levels were 7.7 (SL) and 12.5 dS/m (SM). Drip irrigation was used with low, medium and adequate irrigation levels representing 60%, 80% and 100% of cotton crop water demand, respectively, and three nitrogen applications, i.e., 206, 275 and 343 kg/hm², accounting for 75%, 100% and 125% of local N application, respectively were used. The multi-objective optimization based on spatial analysis showed that, at SL salinity, water use efficiency (WUE), nitrogen use efficiency (NUE), economic benefit and yield simultaneously reached more than 85% of their maxima at 379.18–398.32 mm irrigation and 256.69–308.87 kg/hm². At SM salinity, WUE, yield and economic benefit simultaneously reached more than 85% of their maxima when irrigation was 351.24–376.30 mm and nitrogen application was 230.18–289.89 kg/hm². NUE, yield and economic benefit simultaneously reached their maxima at 428.01–337.72 mm irrigation, and nitrogen application range was 222.14–293.93 kg/hm². The plants at SL salinity had 21.58%–46.59% higher WUE rates, 14.91%–34.35% higher NUE rates and 20.71%–35.34% higher yields than those at SM salinity. The results are of great importance for the nutrient and water management in cotton field in the arid saline area.

Keywords: cotton growth; multi-objective optimization; soil salinization; water and nitrogen regulation; spatial analysis

1 Introduction

Saline soil is distributed in nearly 100 countries in the world, with a total area of about 1×10^9 hm^2, accounting for about 25% of the total land area; additionally, about 3×10^5 hm^2 of arable land is developing toward secondary salinization every year. Soil salinization has become one of the main causes of land degradation in arid areas, seriously affecting the sustainable development of agriculture and the stability of oasis ecological environment (Adiku et al., 2001; Hou et al., 2009).

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Xinjiang, located in the arid and semi-arid areas of Northwest China, has a low precipitation and high evaporation, with a salinized area accounting for about 1/3 of the cultivated land area and a low land utilization rate that seriously restricts the development of agriculture (Wang et al., 2011; Wang et al., 2018). Because of its high salt tolerance and effective use of saline-alkali land resources, cotton has become the largest cash crop in Xinjiang, accounting for 78% of the country's total agricultural area and 85% of the country's output (Wang et al., 2012).

Water and nitrogen are important factors affecting cotton yield and quality. Reasonable irrigation and nitrogen application can significantly improve cotton yield, quality and economic benefit (Jiang et al., 1995). Due to excessive soil salinization resulting in cotton growth inhibition and exacerbating premature senescence, farmers increase their nitrogen application to ensure normal growth of cotton, which causing problems such as waste of resources and environmental pollution. Therefore, in the process of development and utilization of saline-alkali land in arid and semi-arid areas, how to give full play to the synergistic coupling effect of water and fertilizer on crop growth and improve cotton planting technology without further deteriorating the ecological environment is an important scientific issue.

The integration of water and fertilizer in drip irrigation transports water and fertilizer to the root zone of crops through the drip irrigation system for absorption and utilization. This irrigation method not only increases crop yield but also effectively reduces losses of water and fertilizer and greatly improves the efficiency of their utilization. Drip irrigation is an important modern agricultural technology that can alleviate the shortage of soil and water resources in arid areas (Dağdelen et al., 2009). In recent years, many scholars in China and elsewhere have performed much research on the regulation of water and nitrogen in cotton. Within a certain threshold range, increasing water and nitrogen application has a synergistic effect on increasing cotton yield. Outside this range, yield may increase marginally or even decline (Wang et al., 2013; Wu et al., 2014; Choudhary et al., 2020).

A reasonable ratio of water and nitrogen not only helps to stabilize yield but also avoids waste of water and fertilizer resources, and reduces the impact of excess fertilizer on the environment. He et al. (2017) and Wang et al. (2018) found that water-nitrogen interaction in the mild saline-alkali soil had a very significant effect on the net photosynthetic rate, transpiration rate and stomatal conductance of cotton at each growth stage, and considered that optimal amount of nitrogen application under irrigation was 3740 m^3/hm^2. Wang et al. (2013) found that a low irrigation level of 60% of crop water demand (ET_c) significantly inhibited any effect of fertilizer; however, an irrigation level of 90% ET_c and nitrogen application of 278 kg/hm^2 maximized cotton seed yield, WUE and net income. Li and Zhang (2012) studied the water-nitrogen coupling effect on cotton under different irrigation levels in the cotton area of Gansu Province, and developed a water-nitrogen model for efficient utilization of water and nitrogen and promoted cotton growth. Wang et al. (2018) studied the coupling effect of different water and fertilizer rates on cotton seed yield, WUE, fertilizer use efficiency and economic benefit in northern Xinjiang. They found that an irrigation range of 213–463 mm and fertilizer application rate (N-P_2O_5-K) of 212.59–367.51 kg/hm^2 resulted in cotton seed yield, economic benefit and WUE simultaneously reaching 90% of their maximum values. Wu et al. (2015) proposed an irrigation range of 328–395 mm and a range of nitrogen application of 250–300 kg/hm^2 as the best irritation and nitrogen levels for cotton planting. Deng et al. (2013) studied the effects of water-nitrogen coupling on cotton yield and water-nitrogen transformation in southern Xinjiang; irrigation of 395 mm and nitrogen application of 300 kg/hm^2 significantly increased WUE, NUE and yield of cotton. Cotton is a crop with a high nitrogen requirement and inappropriate nitrogen application causes overgrowth and premature senescence, which affects yield and quality. Min et al. (2014) suggested that the application of N fertilizer (0–360 kg/hm^2) could alleviate salt damage, promote cotton growth and increase both cotton yield and WUE.

Salt stress on cotton results in reduced leaf area, thinner stems and lowered dry matter. Chen et al. (2020) found that with the increase in soil salinity content, the cotton dry matter, boll number per plant, boll weight and lint yield decreased. Krishnamurthy et al. (2016) found that cotton yield began to decrease at a soil salinity threshold of 7.7 dS/m, and decreased by 5.2% with an increase

in salinity of 1.0 dS/m. Xue et al. (2007) studied the effect of water-nitrogen coupling on sunflower growth in salinized soil and found that water was the main factor affecting growth, followed by salt stress and then nitrogen. Although many studies have investigated cotton planting and growth in saline-alkali soil (Zhang et al., 2017), they have focused on improving soil and fertilizer use efficiencies (Du et al., 2017; Luo et al., 2017). Studies of water-nitrogen coupling have mainly focused on the main food crops in non-salinized areas, and there are few studies on the physiological growth of cotton under salt stress in arid areas. For cotton cultivated on saline land with limited water resources, effective irrigation and fertilization are very important for physiological growth, dry matter, quality, WUE, PFP (nitrogen partial factor productivity), NUE, yield and economic benefit.

In this paper, using spatial analysis (Thompson and Doerge, 1996; Lin et al., 2019), we carried out the horizontal projection of three-dimensional surface obtained by multiple regression equation of each index to find the overlap of acceptable regions of each target (≥85% maximum) and obtained the optimal combination range of each index. Based on multiple regression analysis of cotton growth indices under drip irrigation and different salt stress, this paper aimed to (1) comprehensively evaluate the yield, quality, water-saving, fertilizer saving and high efficiency of cotton combined with spatial analysis method; (2) propose an optimal water-nitrogen coupling model for the above indices; and (3) reveal the response of cotton growth to water and nitrogen regulation under salt stress.

2 Materials and methods

2.1 Study area

The field experiment was carried out in Beiquan Town (43°21′–45°20′N, 84°43′–86°35′E), Shihezi City, Xinjiang Uygur Autonomous Region, China during the cotton-growing period of May–November in 2018 and 2019. The elevation of the site is 412 m, the average surface slope is 6% and the depth of groundwater is more than 5 m. Average annual precipitation is 198 mm, average mean temperature is 7.5°C–8.2°C, annual average wind speed is 1.5 m/s, average annual sunshine time is 2865 h, and the accumulated temperature for ≥10°C is 3463°C. The average evaporation is 1340 mm. The soil is sandy loam with 43% saturation moisture content, 30% water holding capacity and 42% soil porosity. The physical properties of 0–100 cm soil depth are shown in Table 1.

Table 1 Soil physical property in the experimental area

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm^3)
0–20	62.65	32.70	4.59	1.46
20–40	63.29	33.92	3.86	1.48
40–60	71.93	21.86	5.60	1.51
60–80	68.92	26.87	4.31	1.49
80–100	73.08	23.68	3.42	1.52

2.2 Experimental design and soil sampling

The average salinity content of 0–100 cm soil layer was measured from different areas of fields in the test area. Two plots (S1 and S2 in Figure 1) with soil salinities of 7.4 and 12.1 dS/m were selected representing low (SL) and medium salinity (SM), respectively.

There were 18 treatments in the experiment, including two salinity levels, three N rates and three irrigation levels with three replicates per treatment. The irrigation levels used in the experiment were: low (I1), medium (I2), and adequate (I3), illustrating 60%, 80% and 100% of cotton ET_c, respectively. The plants were fertilized using three nitrogen levels, i.e., 206 (N1), 275 (N2), and 343 (N3) kg/hm^2, accounting for 75% (low), 100% (medium), and 125% (high) of local N application, respectively. Each plot size was 4.6 m×6.0 m (width×length).

The drip irrigation under plastic mulching method was used in the field as shown in Figure 2. The

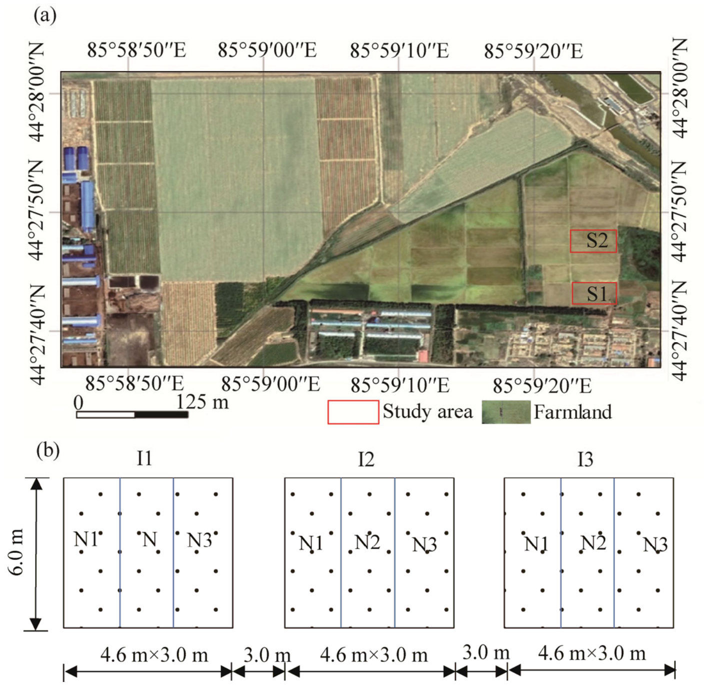

Fig. 1 Location of the study area (a) and experimental design (b) in the field. N1, N2 and N3 represent nitrogen application levels. I1, I2 and I3 represent irrigation levels. The detailed treatments of nitrogen and irrigation are shown in Table 2.

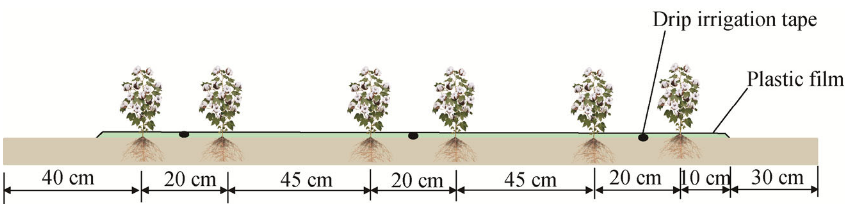

Fig. 2 Cotton planting pattern and schematic diagram of drip irrigation

drip irrigation laterals used were single-wing labyrinth emitters with an internal diameter of 16.0 mm, 0.3 m emitter interval, and 3.2 L/h average flow rate of the emitter. A water meter, ball valve and fertilizer tank were separately installed at the head of each field experiment to accurately control water and nitrogen consumption. Cotton variety 'Xinluzao 7' was sown at 3–4 cm depth on 15 April, 2018 and 1 May, 2019. The planting density of cotton was 181,909 plants/hm^2.

Fertilizers of phosphate (P_2O_5; 100 kg/hm^2), potassium (K_2O; 100 kg/hm^2) and 30% of N (20% of conventional urea and 10% of ^{15}N-urea) were applied, and the remaining 70% of N fertilizer was applied with irrigation at different times during cotton growth stages (Table 2). ^{15}N-urea, with an abundance of 5.16%, was purchased from Shanghai Research Institute, China.

In this experiment, water requirement of cotton was devised using the following formula:

$$ET_c=K_c\times ET_0, \tag{1}$$

where ET_c is the water demand (mm) of the crop in a certain period; ET_0 is the reference crop evapotranspiration (mm); and K_c is the crop coefficient to the corresponding growth period. In this experiment, ET_c values for cotton seedling, flower bud, flower and boll, and boll opening stages were taken as 0.35, 0.76, 1.18 and 0.60, respectively (Wang et al., 2016). ET_0 was calculated using the Penman-Monteith equation (Allen et al., 1998):

$$ET_0=\frac{0.408\Delta(R_n-G)+\gamma\dfrac{900}{T+273}\mu_2(e_s-e_a)}{\Delta+\gamma(1+0.3\mu_2)}, \tag{2}$$

where R_n is the ground net radiation evaporation equivalent (MJ/(m^2•d)); G is the soil heat flux (MJ/(m^2•d)); γ is the psychometric constant (kPa/°C); T is the average temperature (°C); μ_2 is the wind speed 2 m above the ground (m/s); e_s is the saturated vapor pressure (kPa); e_a is the water pressure (kPa); and Δ is the slope of the saturated vapor pressure temperature curve (kPa/°C). All parameters in the formula were provided by the Shihezi Meteorological Bureau, China.

Table 2 Irrigation and nitrogen application in the study

Irrigation time	Irrigation date	Growth stage	ET_0 (mm)	K_c	Irrigation amount (mm)			Nitrogen application level (kg/hm^2)		
					I1	I2	I3	N1	N2	N3
2018										
1	15 Apr	Sowing seeds			40.00	55.00	65.00	61.80	83.00	102.90
2	1 May	Seedling stage	93	0.35	19.53	26.04	32.55	6.18	8.30	10.29
3	1 June	Seedling stage	85	0.35	17.85	23.80	29.75	6.18	8.30	10.29
4	11 Jun	Seedling stage	110	0.35	23.10	30.80	38.50	6.18	8.30	10.29
5	17 Jun	Flower bud stage	72	0.76	32.83	43.78	54.72	14.42	19.30	24.01
6	1 Jul	Flower bud stage	73	0.76	33.29	44.38	55.48	14.42	19.30	24.01
7	14 Jul	Flower and boll	50	1.18	35.40	47.20	59.00	30.90	41.30	51.45
8	31 Jul	Flower and boll	52	1.18	36.82	49.09	61.36	30.90	41.30	51.45
9	9 Aug	Flower and boll	43	1.18	30.44	40.59	50.74	30.90	41.30	51.45
10	3 Sep	Boll opening	56	0.60	20.16	26.88	33.60	4.12	5.50	6.86
Total					289.42	387.56	480.70	206.00	275.00	343.00
2019										
1	1 May	Sowing seeds			40.00	55.00	65.00	61.80	83.00	102.90
2	20 May	Seedling stage	87	0.35	18.27	24.36	30.45	6.18	8.30	10.29
3	15 Jun	Seedling stage	90	0.35	18.90	25.20	31.50	6.18	8.30	10.29
4	20 Jun	Seedling stage	115	0.35	24.15	32.20	40.25	6.18	8.30	10.29
5	24 Jun	Flower bud stage	80	0.76	36.48	48.64	60.80	14.42	19.30	24.01
6	10 Jul	Flower bud stage	74	0.76	33.74	44.99	56.24	14.42	19.30	24.01
7	14 Jul	Flower and boll	56	1.18	39.65	52.86	66.08	30.90	41.30	51.45
8	31 Jul	Flower and boll	50	1.18	35.40	47.20	59.00	30.90	41.30	51.45
9	9 Aug	Flower and boll	40	1.18	28.32	37.76	47.20	30.90	41.30	51.45
10	3 Sep	Boll opening	50	0.60	18.00	24.00	30.00	4.12	5.50	6.86
Total					292.92	392.22	486.52	206.00	275.00	343.00

Note: ET_0 is the reference crop evapotranspiration; K_c is the crop coefficient.

2.3 Data analysis

2.3.1 Dry matter

Four cotton plants were randomly taken at different growth stages from each treatment. The roots, stems, leaves, buds and bolls were dried in an oven at 75°C to a constant weight. Dry matter was determined using precision electronic weighing. Finally, cotton dry matter was calculated as follows: dry matter per hectare=average dry matter of five cotton plants×planting density per hectare (Umbetaev et al., 2015).

2.3.2 Boll weight and yield

At the harvest period, 30, 40 and 30 bolls were collected from 7 upper branches, 4–6 middle branches and 1–3 lower branches, respectively. The 100 cotton bolls were weighed and actual yield was calculated for each plot. Cotton seeds were weighed and yield per hectare was calculated by multiplying planting density per hectare (Li et al., 2019).

2.3.3 Harvest index (HI)

The formula for HI is as follows:

$$HI=Y/DMW, \tag{3}$$

where Y is the cotton seed yield (kg/hm^2); and DMW is the above-ground dry matter (kg/hm^2) (Zhang et al., 2012).

2.3.4 WUE

The formula for WUE is as follows:

$$WUE=Y/ET, \tag{4}$$

where Y is the cotton seed yield (kg/hm^2); and ET is the actual water consumption of the crop (mm):

$$ET=Pr+U+I-D-R-\Delta W, \tag{5}$$

where Pr is the precipitation during growth period (mm); U is the groundwater recharge (mm); I is the irrigation (mm); D is the deep seepage amount (mm); R is the runoff (mm); and ΔW is the change in soil water storage before sowing and after harvest (mm). Before cotton planting and after harvesting, soil samples (0–100 cm) were collected from middle and bare lands of each test plot. Soil moisture was measured by soil drying method, and average value was taken. Due to the depth of groundwater, flat terrain and low rainfall, U, R and D were ignored during growth period (Lin et al., 2019).

2.3.5 NUE

^{15}N isotope tracer method was used to calculate NUE (Li et al., 2019). The formulas for NUE are as follows:

$$\text{N uptake by plant part}=\text{dry weight of plant part}\times\text{total N content in test plant part}, \tag{6}$$

$$\text{N uptake by crops}=\text{N uptake of aboveground part}+\text{root N uptake}, \tag{7}$$

$$^{15}\text{N atom percentage excess}={}^{15}\text{N abundance of samples or in }{}^{15}\text{N-urea}-\text{natural abundance of }{}^{15}\text{N}, \tag{8}$$

$$\text{Ndff}={}^{15}\text{N atom percentage excess of test plant part}/{}^{15}\text{N atom percentage excess of }{}^{15}\text{N-urea}, \tag{9}$$

$$^{15}\text{N-urea N uptake by test plant part}=\text{N uptake by test plant part}\times\text{Ndff of test plant part}, \tag{10}$$

$$^{15}\text{N-urea N uptake by crops}={}^{15}\text{N-urea N of aboveground parts}+{}^{15}\text{N-urea N uptake of root}, \tag{11}$$

$$\text{NUE}={}^{15}\text{N-urea N uptake by crops}/{}^{15}\text{N-urea N application rate}\times100\%. \tag{12}$$

Total N content of sample was determined by the Kjeldahl method and ^{15}N abundance was determined by the stable isotope mass spectrometer (MAT-253).

2.3.6 Nitrogen partial factor productivity (PFP)

The formula for PFP is as follows (Ierna et al., 2011):

$$PFP=Y/N, \tag{13}$$

where N is the total amount of applied nitrogen (kg/hm^2).

2.3.7 Cotton fiber quality

The cotton samples (about 20 g) were randomly collected during cotton boll opening period from each plot and micronaire value was determined from the Cotton Quality Testing Center, Ministry of Agriculture, Xinjiang Uygur Autonomous Region, China. The cotton fiber samples were analyzed using a high volume instrument fiber detector in a constant temperature and humidity laboratory (Chen et al., 2016).

2.3.8 Economic benefit (E)

The formula for E is as follows (Wang et al., 2018):

$$E=G-W-F-K-L, \tag{14}$$

where G is the gross profit; W is the irrigation cost; F is the fertilizer cost; K is the manual machinery cost; and L is the land leasing cost (all units are USD/hm^2).

2.4 Data processing

The value of each index was the average of three replicates in each treatment. Data Processing System was used for the analysis of variance and Duncan's test, with significance considered to be

P<0.05 level. MATLAB 2017 and Origin 2019 were used to perform multiple regression, extreme value solution and drawing.

3 Results

3.1 Boll weight, dry matter, yield and HI of cotton

For both years, irrigation-salinity interaction had a significant effect on boll weight, dry matter, yield and HI of cotton, and nitrogen-salinity interaction had significant effects on dry matter and yield. Irrigation-nitrogen interaction had significant effects on boll weight and HI (Table 3). At SL salinity for both years, there was a significant difference in boll weight among N1, N2 and N3 treatments under I1 irrigation, but no significant difference among N1, N2 and N3 treatments under I2 or I3 irrigation. Under the same nitrogen level, boll weight initially increased and then decreased with the increase in irrigation (Fig. 3a and b). At SM salinity for both years, there were significant differences among N1, N2 and N3 treatments under I2 irrigation, and boll weight was significantly higher for N2 than for N3 treatment.

Table 3 ANOVA results for boll weight, dry matter, yield and harvest index (HI)

Treatment	Boll weight		Dry matter		Yield		HI	
	2018	2019	2018	2019	2018	2019	2018	2019
I×S	**	**	**	**	**	**	**	**
N×S	ns	ns	*	*	*	*	ns	ns
I×N	*	*	**	**	**	**	*	*
I×N×S	ns	ns	*	*	ns	ns	ns	ns

Note: I, irrigation; S, salinity; N, nitrogen; *, *P*<0.05 level; **, *P*<0.01 level; ns, no significant difference.

Dry matter was much lower at SM salinity than at SL salinity (Fig. 3c and d). For both years, dry matter increased with the increase in irrigation at the same salinity level. The maximum dry matter for both years at SL salinity was about 1.66-fold higher than that at SM salinity. At SL salinity for both years, dry matter initially increased and then decreased with the increase in nitrogen application at the same irrigation level, and there was a significant difference in dry matter between I1 and I3 for N1, N2 and N3 treatments. At SM salinity for both years, under all irrigations, dry matter was significantly higher for N1 than for N3 treatment, indicating that under the double stresses of water and salt, higher nitrogen application did not alleviate salt stress, but aggravated stress on cotton. At the same irrigation level, the difference in dry matter among nitrogen levels was less in 2019 (Fig. 3d) than in 2018 (Fig. 3c).

At SM salinity for both years, cotton yield under different water and nitrogen treatments was lower than that of SL salinity, indicating that salt stress reduced cotton yield (Fig. 3e and f). At different salinity levels, cotton seed yield was lower under I1 than under other irrigation levels, indicating that water is the main factor restricting cotton yield under salt stress. At SL salinity for both years, yield showed an initial increase followed by a decrease with increasing nitrogen application under I1, indicating that continuous increase in nitrogen application made little contribution to the increase in yield. In both years, the yield was higher under I2 than under I1 irrigation, indicating that water deficit affected fertilizer efficiency.

Irrigation had significant interactions with salinity and nitrogen for HI in 2018 and 2019 (Table 3). HI values at SL and SM salinities ranged from 0.35 to 0.42 and from 0.33 to 0.36, respectively (Fig. 3g and h). At SL salinity for two years, HI value initially increased and then decreased with the increase in irrigation at the same nitrogen level, indicating that the contribution of irrigation was greater to vegetative organs than to seeds. At SM salinity for two years, HI values under I1 and I3 irrigations were lower than that for I2 in 2019, indicating that water deficit and excess water were not conducive to transport from vegetative organs to reproductive organs under salt stress. For N1 treatment, total dry matter accumulation of plants was lower and cotton seed yield was lower than that of boll weight.

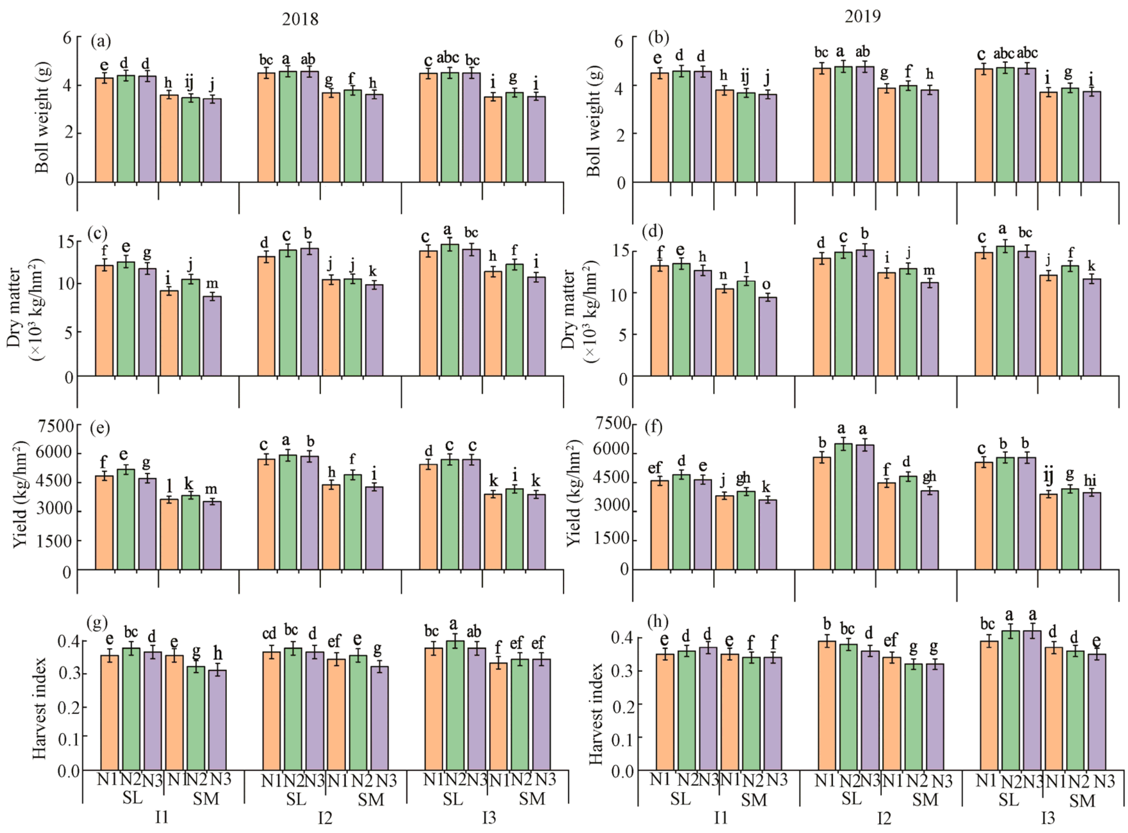

Fig. 3 Effects of water-nitrogen coupling on boll weight (a and b), dry matter (c and d), yield (e and f), and harvest index (g and h) of cotton under salt stress. Bars indicate standard errors. Different lowercase letters indicate significant difference among different treatments at *P*<0.05 level according to Duncan's test. N1, N2 and N3 represent nitrogen application levels. I1, I2 and I3 represent irrigation levels. The detailed treatments of nitrogen and irrigation are shown in Table 2. SL and SM represent 7.7 and 12.5 dS/m salinity levels, respectively.

3.2 Cotton quality

All interactions among irrigation, nitrogen and salinity significantly affected micronaire values in both years (Table 4). At SL salinity, micronaire value increased with increasing nitrogen application at the same irrigation level. For N2 and N3 treatments, micronaire value decreased with the increase in irrigation. Micronaire value was significantly higher for N3 than for N1 and N2 treatments at SL salinity. Micronaire value was significantly higher for I1 than for I2 and I3 irrigations (except for N1 in 2018). For two years, at the same irrigation level, micronaire value initially increased and then decreased with increasing nitrogen application, and was significantly higher for N2 than for N1 and N3 treatments (Fig. 4a and b). At SL salinity, micronaire value reached the peak range of 5.03–4.71 for N3 treatment (I1N3), while micronaire value reached the peak range of 4.35–4.59 for N2 treatment at SM salinity.

Table 4 ANOVA results for micronaire value and fiber length

Treatment	Micronaire value		Fiber length	
	2018	2019	2018	2019
I×S	**	**	*	*
N×S	**	**	ns	ns
I×N	**	**	*	*
I×N×S	*	*	*	*

Note: I, irrigation; S, salinity; N, nitrogen; *, *P*<0.05 level; **, *P*<0.01 level; ns, no significant difference.

For both years, nitrogen-irrigation coupling had significant effects on fiber length, but the effect of nitrogen application on fiber length was not significant (Table 4). For both salinity levels, there was no significant difference in fiber length between N2 and N3 under I3, but under I1, it was significantly longer for N2 than for N1 and N3 treatments (Fig. 4c and d). Under the same nitrogen application, fiber length initially increased and then decreased with the increase in irrigation under two salinity levels. Too much or too little water and nitrogen hinder plant nitrogen metabolism, leading to premature senescence or reduced cotton fiber quality. Therefore, appropriate amounts of water and nitrogen will optimize fiber quality. For both years, the maximum value of cotton fiber length at SL salinity was 28.25 mm, which was 6.24% higher than the minimum fiber length. At SM salinity, the maximum fiber length was 26.21 mm, which was 8.36% higher than the minimum fiber length.

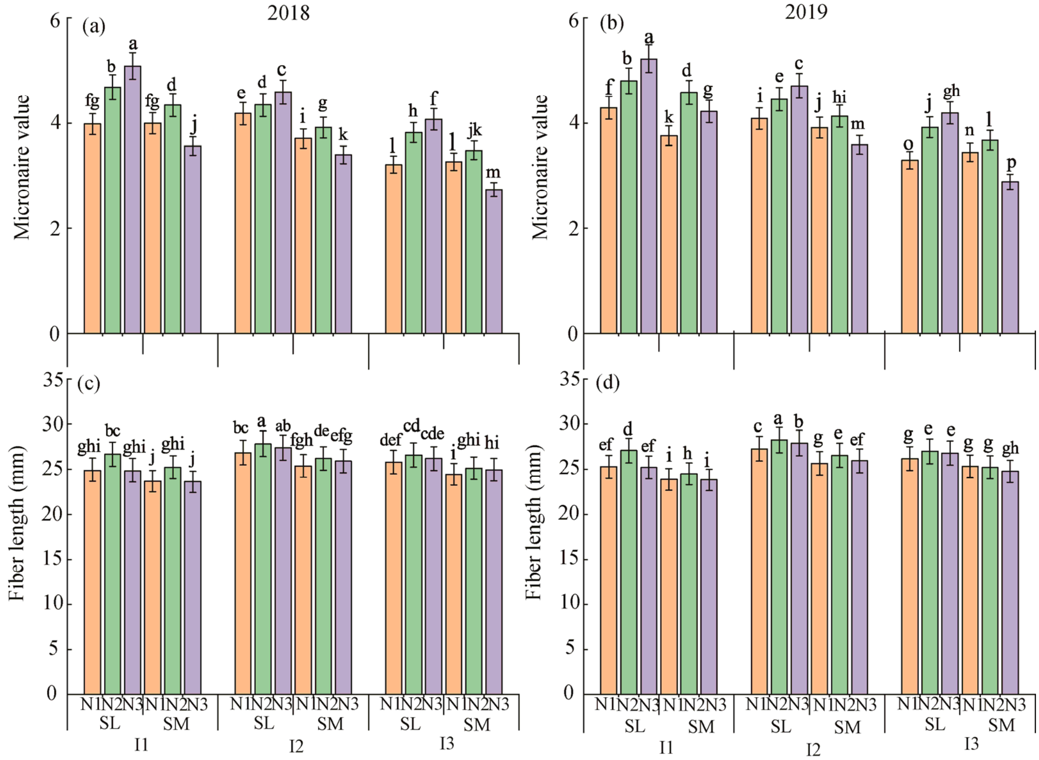

Fig. 4 Effects of water-nitrogen coupling on micronaire value (a, b) and fiber length (c, d) of cotton under salt stress. Bars indicate standard errors. Different lowercase letters above the bars indicate significant difference among different treatments at $P<0.05$ level according to Duncan's test. N1, N2 and N3 represent nitrogen application levels. I1, I2 and I3 represent irrigation levels. The detailed treatments of nitrogen and irrigation are shown in Table 2. SL and SM represent 7.7 and 12.5 dS/ m salinity levels, respectively.

3.3 WUE, PFP and NUE

For both years, interaction among irrigation, nitrogen and salinity had a significant effect on WUE, PFP and NUE (Table 5). At SL salinity, WUE decreased with the increase in irrigation within the same nitrogen level. And the effect of nitrogen application on WUE was N2>N1>N3 under I1 and I3 irrigations (Fig. 5a). At SM salinity, WUE initially increased and then decreased with rising nitrogen application under I1 and I2 irrigations, and WUE was significantly higher in 2019 than in 2018 (Fig. 5a and b). Under I3 irrigation, WUE was significantly higher for N2 than for N1 and N3 treatments. Among treatments, the highest WUE at SL and SM salinities occurred under I1 and N2 treatments, with values of 0.81–1.68. At the same nitrogen level, only low water and high fertilizer levels improved WUE.

At SL salinity, the maximum value of PFP occurred at I2 and N1 treatment (Fig. 5c and d). At the same irrigation level, PFP decreased gradually with the increase in nitrogen application. For N1 and N2 treatments, PFP initially increased and then decreased with the increase in irrigation.

At SL salinity, there were significant differences in PFP among N1, N2 and N3 treatments under the same irrigation level. The high water and low fertilizer were beneficial for improving PFP.

Table 5 ANOVA results for water use efficiency (WUE), nitrogen partial factor productivity (PFP) and nitrogen use efficiency (NUE)

Treatment	WUE		PFP		NUE	
	2018	2019	2018	2019	2018	2019
I×S	**	**	*	*	*	*
N×S	**	**	ns	ns	**	**
I×N	**	**	*	*	*	*
I×N×S	*	*	*	*	*	*

Note: I, irrigation; S, salinity; N, nitrogen; *, $P<0.05$ level, **, $P<0.01$ level; ns, no significant difference.

NUE significantly differed under I2 and I3 irrigations at SL salinity (Fig. 5e and f). Under I3 irrigation, NUE increased with an increase in nitrogen application. At the same nitrogen level, NUE initially increased and then decreased with the increase in irrigation. At SM salinity, there were significant differences in NUE among different nitrogen treatments, and the highest NUE was found under I2 and N2 treatments. Proper irrigation can increase NUE of cotton. The appropriate amount of water and nitrogen can increase fertilizer efficiency. Too much nitrogen will increase soil salinity and aggravate secondary salinization; on the country, less nitrogen will not meet the demand for cotton physiological growth.

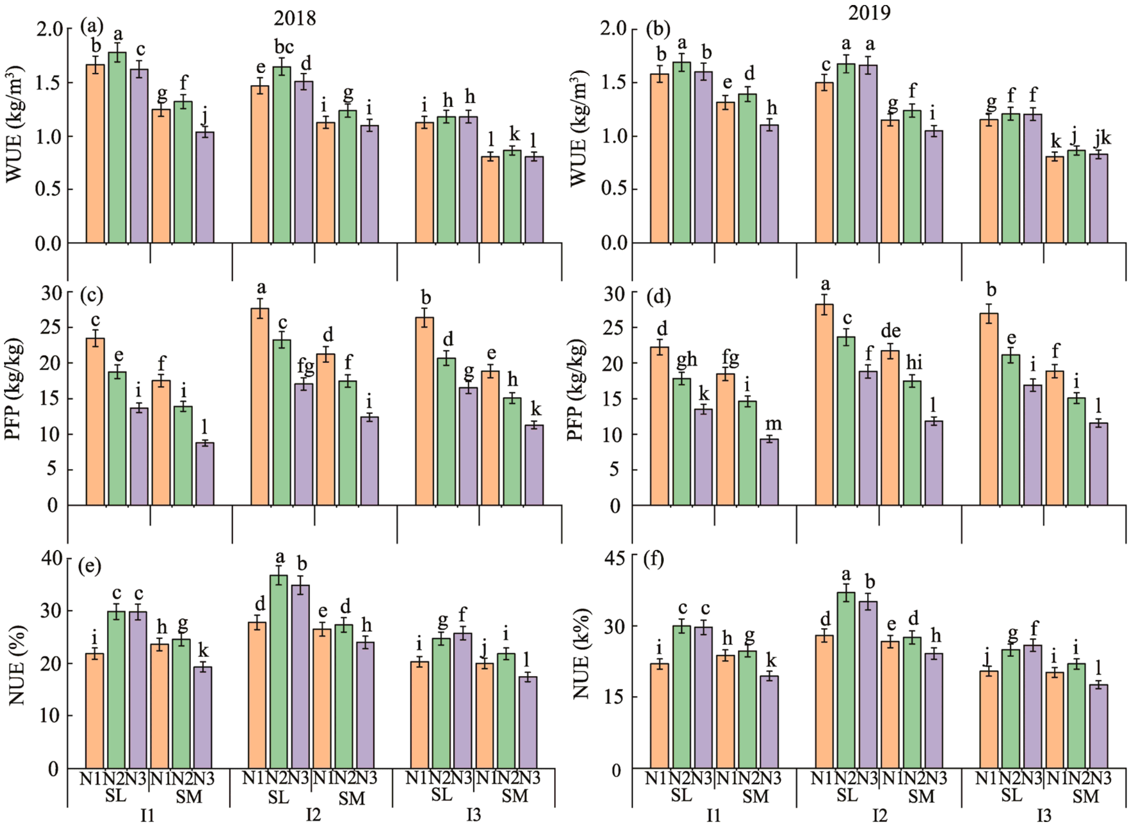

Fig. 5 Effects of water-nitrogen coupling on water use efficiency (WUE; a and b), nitrogen partial factor productivity (PFP; c and d) and nitrogen use efficiency (NUE; e and f) of cotton under salt stress. Bars indicate standard errors. Different lowercase letters above the bars indicate significant differences among different treatments at $P<0.05$ level according to Duncan's test. N1, N2 and N3 represent nitrogen application levels. I1, I2 and I3 represent irrigation levels. The detailed treatments of nitrogen and irrigation are shown in Table 2. SL and SM represent 7.7 and 12.5 dS/m salinity levels, respectively.

3.4 Economic benefit

The gross costs in 2018 and 2019 at SL salinity were 5449.00–7399.36 and 840.89–1141.88 USD/hm^2, respectively (Table 6). At SL salinity, the highest gross cost was increased by 14.6% and 49.0% compared with the lowest gross cost, the lowest economic benefits were 840.89 and 571.37 USD/hm^2, and the highest economic benefits were 91691.16 and 2268.70 USD/hm^2 in 2018 and 2019, respectively. At SM salinity, the lowest economic benefits were 152.63 and 196.13 USD/hm^2 in 2018 and 2019, respectively, and correspondingly the highest economic benefits were 1252.36 and 1251.64 USD/hm^2. These results showed that appropriate management of water and fertilizer can affect gross profit and double economic benefit. Difference between the highest and the lowest economic benefits at SM salinity was 4.14 times that of SL salinity. Although the cost of land leasing accounts for a small proportion of the total investment, salt stress leads to great economic losses for cotton, which is one of the main reasons that farmers prefer to rent land with the high cost and low salinity content.

Table 6 Effect of water-nitrogen coupling on economic benefit of cotton under salt stress

Treatment	2018					2019				
	Irrigation cost	Fertilizer cost	Land leasing	Gross profit	Economic benefit	Irrigation cost	Fertilizer cost	Land leasing	Gross profit	Economic benefit
	(USD/hm^2)					(USD/hm^2)				
SLI1N1	156.64	445.06	1388.89	5591.67	862.91	158.26	445.06	1388.89	5292.26	816.71
SLI1N2	156.64	594.14	1388.89	5970.07	921.31	158.26	594.14	1388.89	5665.44	874.30
SLI1N3	156.64	741.05	1388.89	5449.00	840.89	158.26	741.05	1388.89	5373.79	829.29
SLI2N1	209.57	445.06	1388.89	6589.09	1016.83	211.73	445.06	1388.89	6720.38	1037.10
SLI2N2	209.57	594.14	1388.89	7399.36	1141.88	211.73	594.14	1388.89	7519.47	1160.41
SLI2N3	209.57	741.05	1388.89	6772.04	1045.07	211.73	741.05	1388.89	7456.38	1150.68
SLI3N1	259.80	445.06	1388.89	6281.01	969.29	263.04	445.06	1388.89	6416.55	990.21
SLI3N2	259.80	594.14	1388.89	6576.60	1014.91	263.04	594.14	1388.89	6708.06	1035.19
SLI3N3	259.80	741.05	1388.89	6569.90	1013.87	263.04	741.05	1388.89	6701.46	1034.18
SMI1N1	156.64	445.06	925.93	4178.03	644.76	158.26	445.06	925.93	4400.26	679.05
SMI1N2	156.64	594.14	925.93	4433.04	684.11	158.26	594.14	925.93	4655.27	718.41
SMI1N3	156.64	741.05	925.93	4162.90	642.42	158.26	741.05	925.93	4261.68	657.67
SMI2N1	209.57	445.06	925.93	5052.26	779.67	211.73	445.06	925.93	5163.38	796.82
SMI2N2	209.57	594.14	925.93	5555.81	857.38	211.73	594.14	925.93	5555.81	857.38
SMI2N3	209.57	741.05	925.93	4925.12	760.05	211.73	741.05	925.93	4702.89	725.75
SMI3N1	259.80	445.06	925.93	4492.57	693.30	263.04	445.06	925.93	4492.57	693.30
SMI3N2	259.80	594.14	925.93	4808.26	742.02	263.04	594.14	925.93	4808.26	742.02
SMI3N3	259.80	741.05	925.93	4483.72	691.93	263.04	741.05	925.93	4594.84	709.08

Note: N1, N2 and N3 represent nitrogen application levels. I1, I2 and I3 represent irrigation levels. The detailed treatments of nitrogen and irrigation are shown in Table 2. SL and SM represent 7.7 and 12.5 dS/ m salinity levels, respectively.

4 Multi-objective optimization

The economic benefit, WUE, NUE and PFP were selected as optimization objectives on the sustainable development of cotton field due to their important effects on yield. The binary quadratic equations based on the least square method were developed for regression analysis under different salinity levels, taking water and nitrogen inputs as independent variables, and yield, economic benefit, WUE, NUE and PFP as dependent variables (Table 7). The effects of water and nitrogen inputs on all dependent variables were significant, and the determination coefficients were all above 0.86. Taking I1 and I3 as the upper and lower limits of irrigation, respectively, and N1 and N3 as the upper and lower limits of nitrogen application, respectively, the maximum values of each equation was obtained by MATLAB extremum problem-solving method, and the maximum irrigation and nitrogen application levels were obtained.

Table 7 Effect of water-nitrogen coupling on cotton yield, economic benefit, water use efficiency (WUE), nitrogen use efficiency (NUE) and nitrogen partial factor productivity (PFP) under salt stress

Variable	Equation	R^2	P
SL yield /Y1	$Y1= -18307+91.06W+40.17N-0.111W^2-0.068N^2-0.00047WN$	0.87	<0.01
SM yield /Y2	$Y2= -10884+56.84W+32.41N-0.067W^2-0.056N^2-0.0096WN$	0.86	<0.01
SL economic benefit/Y3	$Y3= -96440+411.99W+187.72N-0.52W2-0.39N^2+0.067WN$	0.95	<0.01
SM economic benefit/Y4	$Y4= -72680+273.16W+203.43N-0.35W^2-0.41N^2+0.018WN$	0.93	<0.01
SL WUE/Y5	$Y5= -1.298+0.0103W+0.11N-1.73\times10^{-5}W^2-1.3\times10^{-5}N^2+2.37\times10^{-6}WN$	0.95	<0.01
SM WUE/Y6	$Y6= -0.81+0.006W+0.10N-1.31\times10^{-5}W^2-2.59\times10^{-5}N^2+8.28\times10^{-6}WN$	0.93	<0.01
SL NUE/Y7	$Y7= -165.03+0.66W+0.052N-8.41\times10^{-4}W^2-7.86\times10^{-4}N^2-9.51\times10^{-5}WN$	0.90	<0.01
SM NUE/Y8	$Y8= -75.78+0.372W+0.275N-5.25\times10^{-4}W^2+5.89\times10^{-4}N^2+6.51\times10^{-5}WN$	0.93	<0.01
SL PFP /Y9	$Y9= -17.08+0.286W-0.065N-3.39\times10^{-4}W^2+8.84\times10^{-6}N^2-2.67\times10^{-5}WN$	0.97	<0.01
SM PFP/Y10	$Y10= -11.15+0.202W-0.0258N-2.71\times10^{-4}W^2-1.06\times10^{-5}N^2+5.61\times10^{-5}WN$	0.98	<0.01

Note: SL and SM represent 7.7 and 12.5 dS/m salinity levels, respectively. W, amount of water used; N, amount of fertilizer used.

At SL salinity, the yield, economic benefit and PFP simultaneously reached the maximum with 410.00–414.00 mm irrigation. At SM salinity, the yield, economic benefit and PFP reached the maximum with 394.00–402.63 mm irrigation. WUE and PFP reached the maximum with 301.12–402.63 mm irrigation and 247.93–264.71 kg/hm^2 nitrogen application (Table 8). Under the same irrigation level, nitrogen application varied greatly, thus it was not possible to have the above indicators simultaneously reaching their maxima under the same irrigation and nitrogen levels.

Table 8 Effects of water-nitrogen coupling on the cotton yield, economic benefit, water use efficiency (WUE), nitrogen use efficiency (NUE) and nitrogen partial factor production (PFP) under salt stress

Dependent variable	Maximum dependent variable		Irrigation		Nitrogen application	
	SL	SM	SL	SM	SL	SM
Yield (kg/hm^2)	6218.12	4705.62	410.17	402.63	295.47	264.71
Economic benefit (USD/hm^2)	2149.29	1166.54	410.22	394.06	275.88	256.33
WUE (kg/m^3)	1.73	1.33	317.29	301.12	276.69	247.93
NUE (%)	36.20	28.10	379.12	371.28	289.28	255.53
PFP (kg/kg)	28.04	20.92	414.26	394.06	206.00	200.80

Note: SL and SM represent 7.7 and 12.5 dS/ m salinity levels, respectively.

Through normalized treatment of each index, we used the spatial analysis to evaluate the acceptable ranges of yield, economic benefit, WUE, NUE and PNP. We found the reasonable acceptance range of 85% at SL and SM salinities, and comprehensively analyzed the contour projection of 85% of the maximum values of WUE, quality, NUE, economic benefit and yield (Figs. 6 and 7). At SL salinity, when WUE, NUE, economic benefit and yield reached the maximum, the range for irrigation was 379.18–398.32 mm and nitrogen application was 256.69–308.87 kg/hm^2 (Fig. 8). At SM salinity, WUE, yield and economic benefit reached their maxima at the ranges of 351.24–376.30 mm irrigation and 230.18–289.89 kg/hm^2 nitrogen application. The range of irrigation for the maximum NUE, yield and the economic benefit was 415.14–437.87 mm and the range of nitrogen application was 222.14–293.93 kg/hm^2.

5 Discussion

5.1 Boll weight, dry matter accumulation, cotton yield and HI

In arid and semi-arid areas, low water and nitrogen input affects cotton growth, however, excessive irrigation and nitrogen application not only reduce WUE, increase the cost and waste

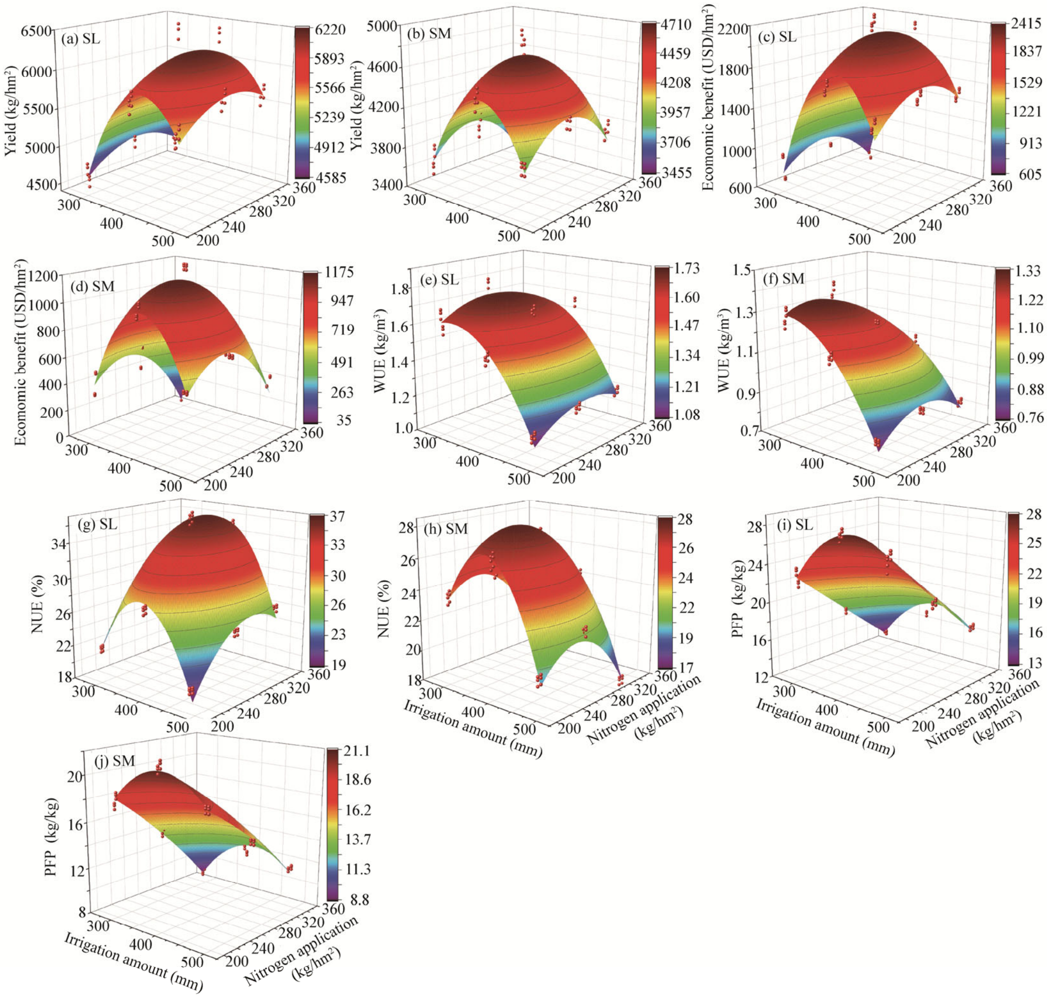

Fig. 6 Effects of water-nitrogen coupling on relationships of cotton yield (a and b), economic benefit (c and d), water use efficiency (WUE; e and f), nitrogen use efficiency (NUE; g and h) and nitrogen partial factor production (PFP; i and j) under salt stress. SL and SM represent 7.7 and 12.5 dS/ m salinity levels, respectively. The red dots in the figure represent the measured values in 2018 and 2019.

resources, but also damage soil structure. Furthermore, excessive fertilization results in underground water pollution, contributes to soil salinization, and increases the negative effect of soil salinity on plant performance (Chen et al., 2010). Water and nitrogen management of cotton can be achieved by coordinating irrigation and nitrogen application to provide the best opportunity to save water and to achieve the high yield and fiber quality.

At low salinity (7.4 dS/m), higher boll weight, plant dry weight and cotton yield were obtained as compared with higher salinity (12.1 dS/m). Seed yields were 27.6% and 27.3% lower at SM than at SL in 2018 and 2019, respectively. Boll weights were 19.6% and 12.2% lower at SM than at SL in 2018 and 2019, respectively. The reduction in boll weight is due to the negative effects of salinity as indicated by the significant negative correlation between soil salinity and cotton yield and its components. Previous studies showed that less cotton yield was related with decreased lint weight per boll and boll number per plant with the increase in soil salinity content (Hu et al., 2010). The fewer bolls per plant might be attributed to the greater chance of shedding due to the nutrient imbalance caused by the high soil salinity (Chen et al., 2010).

In our study, the effect of salt stress on cotton boll weight fluctuated with the changes in nitrogen application and irrigation levels. Cotton yield is the important index to evaluate different

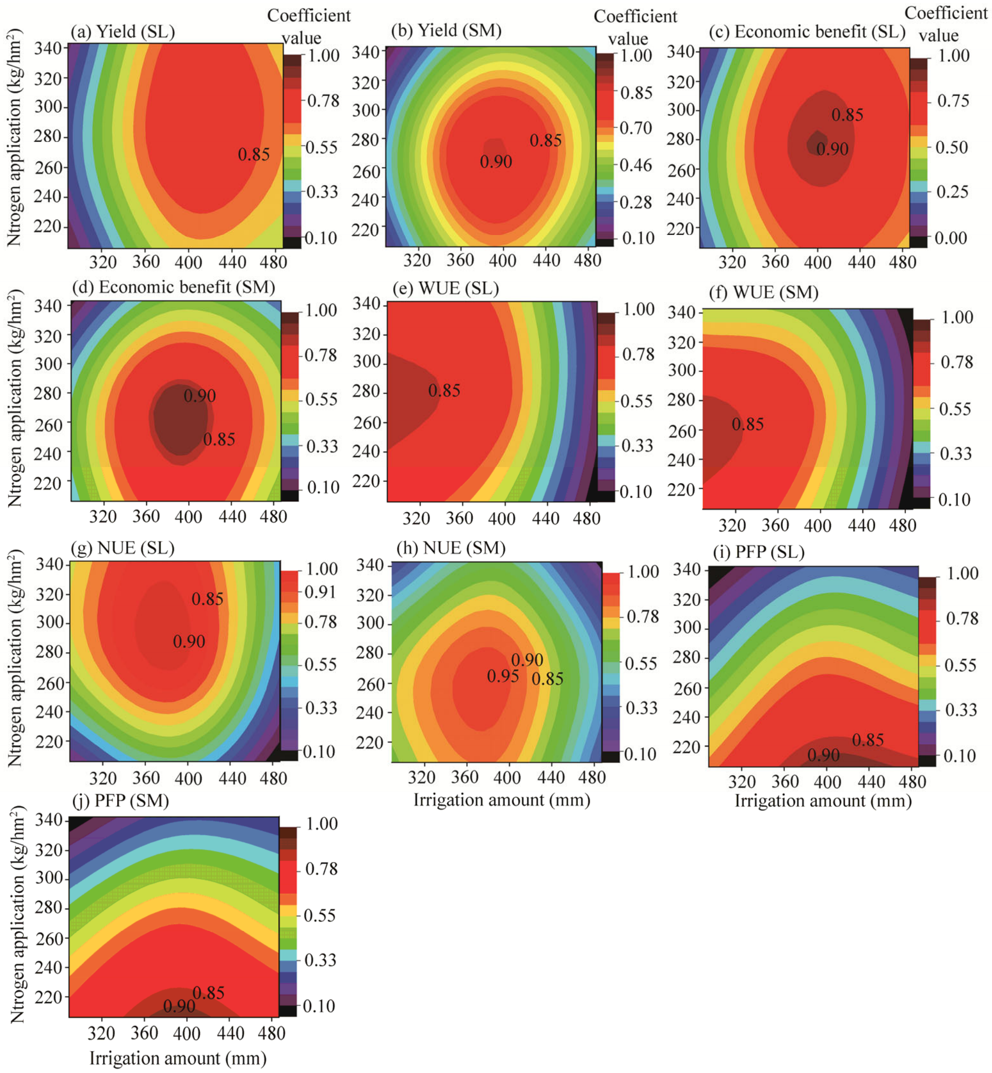

Fig. 7 Effects of water-nitrogen coupling on cotton yield (a and b), economic benefit (c and d), water use efficiency (WUE; e and f), nitrogen use efficiency (NUE; g and h) and nitrogen partial factor production (PFP; i and j) under salt stress. SL and SM represent 7.7 and 12.5 dS/ m salinity levels, respectively.

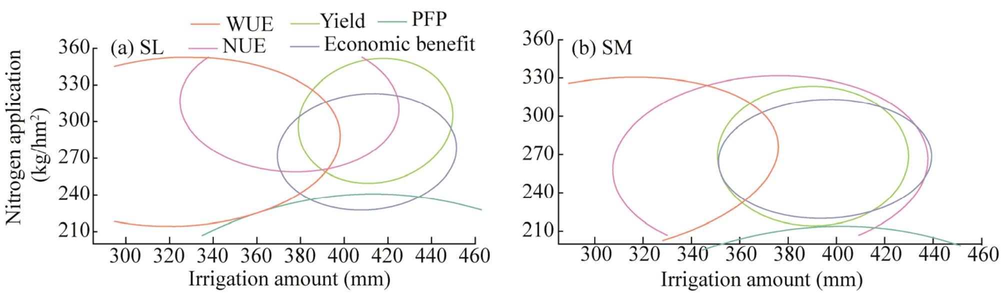

Fig. 8 Effects of water-nitrogen coupling on comprehensive evaluation of different indices under salt stress. WUE, water use efficiency; NUE, nitrogen use efficiency; PFP, nitrogen partial factor production. SL and SM represent 7.7 and 12.5 dS/ m salinity levels, respectively.

water and nitrogen levels under salt stress. Nevertheless, our results indicated that the adverse effects of soil salinity on cotton growth could be alleviated by nitrogen application, but excessive nitrogen application at SM salinity inhibited the expansion of cotton growth, leading to a decrease

in the boll weight and seed yield as indicated by the least dry matter for N3 and the highest dry matter for N2. The highest seed yield was found for N2 and seed yield was 5003 kg/hm^2 in 2018 and 5027 kg/hm^2 in 2019. While seed yield was 9.0% and 6.8% less for N3 than for N1 in 2018 and 2019, respectively. The results suggested that over-fertilization increased the negative effects of soil salinity on plant performance and might contribute to soil salinization (Chen et al., 2010). The results of this study were consistent with those of previous studies in which aboveground dry matter initially increased and then decreased with the increase in nitrogen application. The 252–255 kg/hm^2 nitrogen is proposed for cotton under saline soil if the water supply meets the crop water requirements (Chen et al., 2020). The reason for this phenomenon may be that excessive nitrogen application inhibited the absorption of other nutrients by cotton organs, and then affected the formation of dry matter (Li and Zhang, 2010).

To determine the optimal dose of nitrogen, the consideration of irrigation is particularly relevant. Similar levels of nitrogen could produce differences in nitrogen utilization and yield depending on water supply (García-López et al., 2016). The amount of irrigation is needed to be considered before determining the optimal nitrogen requirement of the crop.

The accumulation of cotton dry matter is the basis for obtaining high-yield and high-quality cotton. Under drip irrigation conditions, increasing the amount of irrigation increased the dry matter accumulation of cotton, but too much water leads to overgrowth. Under different salinity levels, seed yield of cotton was lower under I1 than under other irrigation levels, indicating that water is the main factor restricting cotton yield under salt stress. The excessive irrigation lowered the crop rhizosphere soil osmotic potential and raised crop transpiration, plant active transport and nutrient absorption, and thus dry matter of aboveground tissues increased (Zou et al., 2020). These results implied that a moderate irrigation application that was 80% of ET_c for cotton under mulched drip irrigation provided advantages in terms of yield and economic benefit in the arid region.

Under salt stress in the arid areas, the effect of water-nitrogen interaction on cotton yield was significant on dry matter, boll weight and yield. This result may be caused by the coupling effect of fertilizer by irrigation and transferring fertilizer by water. A higher cotton yield can be achieved by promoting the effect of water and nitrogen. Previous results revealed that cotton yield with drip irrigation increased with the increase in irrigation and fertilizer application within a certain range and then yield declined beyond a certain threshold. Overall, in the two-year study, the maximum dry matter and yield at SL and SM salinities occurred under I2 and N2 treatment. The appropriate combination of water and nitrogen is required to properly utilize the resources and a proper irrigation level could improve plant capability to utilize the applied nitrogen (Sui et al., 2017). Furthermore, the fiber length, NUE and HI also reached the maximum under I2 and N2 treatment. However, the highest N (I1) and the lowest irrigation (N3) treatment produced the lowest dry matter, boll weight and seed yield, indicating that less water supply reduces the availability of nitrogen to cotton. Tang et al. (2005) found that less water supply lessened the yield and biomass accumulation due to stomatal closure and decreased photosynthesis. At the same time, under the highest irrigation (I3) and the lowest nitrogen (N1) treatment, the lowest WUE, NUE and micronaire values occurred because high irrigation could cause hypoxia and nutrient leaching. However, dry matter was the highest under I3 and N2 treatment in both years, which indicated that the higher irrigation improved vegetative growth and inhibited reproductive growth (Pinnamaneni et al., 2021). Thus, suitable water and fertilizer can increase cotton yield, which is consistent with other results (Dağdelen et al., 2009).

HI values were lower under I1 and I3 irrigations than under I2 irrigation, indicating that both water deficit and excess irrigation are not conducive to transport nutrients from vegetative organs to reproductive organs of cotton under salt stress (García-López et al., 2016). In our study, at SL salinity, the maximum yield (6218.20 kg/hm^2) was obtained when the amount of irrigation and nitrogen application was 410.17 mm and 295.47 kg/hm^2, respectively. At SM salinity, yield reached the maximum of 4705.62 kg/hm^2 when the amount of irrigation and nitrogen application was 402.63 mm and 264.71 kg/hm^2, respectively. Cotton yield was 32.14% higher at SL than at SM salinity.

5.2 Cotton quality

Fiber quality is one of the main indicators determining the economic benefit of cotton besides yield. Cotton quality is mainly composed of micronaire value and fiber length. High micronaire values (>5.0) indicate irregular coarse fibers, while low values (<3.5) show immature fibers (Kljun et al., 2014). In this study, micronaire value and fiber length decreased with the increase in soil salinity. Previous study of the effect of soil salinity on final quality of cotton fiber is not consistent. Feng et al. (2014) found that soil salinity had a significant positive correlation with micronaire value, but no significant correlation with fiber length. Latif et al. (2019) found that the fiber length uniformly increased with the increase in soil salinity, but the fiber strength and maturity decreased at high salinity. Our study showed that nitrogen increased the fiber length and micronaire value at a medium dose, while fiber length and micronaire value decreased with the increase in irrigation. The formation of fiber length is determined by the rate and duration of fiber elongation. Zhao et al. (2012) found that increasing nitrogen before flowering stage of cotton increased the duration of fiber elongation and maximized elongation rate. In this study, micronaire value reached the highest under I1 irrigation, but the lowest under I3 irrigation. Previous studies showed that micronaire value and irrigation levels are negatively correlated (Sobrinho et al., 2015; Pinnamaneni et al., 2021). Higher irrigation or nitrogen causes immature fiber (Leal et al., 2020). This result could be attributed to the more vegetative growth and less reproductive growth under the higher irrigation level (Pinnamaneni et al., 2021).

5.3 WUE, PFP and NUE

Under the same irrigation levels, nitrogen application can effectively improve WUE. Research has shown that increasing the amount of fertilizer can improve WUE within a certain threshold (García-López et al., 2016). The reason is that nitrogen application promotes the growth of cotton and increases available water in the soil. The available water moves to the vicinity of cotton root system, increasing absorption efficiency and further improving the effective use of soil water (Choudhary et al., 2020). Nitrogen application also had a great effect on PFP. PFP decreased with the increase in nitrogen application under different irrigation levels. Similar results were reported by Ye et al. (2007) and Badr et al. (2016), who reported the maximum PFP occurred at the lowest nitrogen application. Although PFP was the highest for N1 treatment under all irrigation levels, it could not meet the requirement of production.

To obtain a higher economic benefit of cotton planting on the saline-alkali land, it is necessary to improve NUE and reduce nitrogen loss. Our results showed that NUE was the maximum when the maximum seed yield and fiber length was achieved at the same irrigation and nitrogen levels. Similarly, Hou et al. (2009) found that under low and medium salinities, increasing the amount of nitrogen up to an appropriate amount could significantly increase nitrogen uptake of cotton. However, excessive nitrogen application did not increase. Under salt stress, the absorption and utilization of nitrogen by cotton depended on the amount of water (Zhang et al., 2013). NUE decreased if water was excessive, possibly because nitrogen was leached into deep soil, so that crop roots could not absorb it.

5.4 Economic benefit

The results showed that under salinized area, the irrigation water accounted for a small proportion of the total cost, and so farmers' awareness of water-saving was not strong, resulting in the waste of water resources that was not conducive to sustainable development. Economic benefit was 1.78–3.45 and 1.18–1.53 times higher under I2 irrigation than under I1 and I3 irrigations at SL salinity, and 2.93–4.44 and 1.82–2.05 times higher at SM salinity. Thus irrigation had a great impact on economic benefit. And moderate increase in nitrogen could significantly increase yield under SM salinity and I1 irrigation, but this was not obvious for I3 irrigation, and there was no obvious or even a downward trend at SL salinity with excessive nitrogen application.

6 Conclusions

A significant negative correlation between soil salinity and cotton yield was found in this study. Thus an optimal water and nitrogen combination could increase cotton dry matter accumulation

and increase boll weight, hence improved cotton yield under salt stress. The results of multiple regression and spatial analysis showed that cotton yield, economic benefit, WUE, NUE and PFP could reach more than 85% of their maximum value. The maximum WUE, NUE, economic benefit and yield were attained at the ranges of 379.18–398.32 mm irrigation and 256.69–308.87/hm^2 nitrogen application at SL salinity, and 428.01–337.72 mm irrigation and 222.14–293.93 kg/hm^2 nitrogen application at SM salinity.

Acknowledgements

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